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by E. V. Zaretsky, H. W. Scibbe, and D. E. Brewe
Lewis Research Center
Cleveland, Ohio

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by E. V. Zaretsky,* H. W. Scibbe, and D. E. Brewe

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio

E-3422

ABSTRACT

Seven self-lubricating retainer materials were evaluated in 40-millimeter-bore ball bearings operating in a 60° R hydrogen gas at 20,000 rpm and with a 200-pound thrust load. The relative wear of six high-temperature bearing cage materials was also determined at 500° and 700° F in a nitrogen-blanketed cage compatibility tester. When used as cages, glass-fiber-filled and bronze-filled PTFE materials provided transfer films on the bearing inner-races for test durations exceeding 10 hours without evidence of race wear at the cryogenic temperature. Minimum cage wear was obtained at cryogenic temperature with the laminated-glass cloth PTFE and the filled PTFE materials. At the elevated temperatures, S-Monel and AISI M-1 materials gave least wear. For these materials wear decreased with increasing material hardness.

INTRODUCTION

In the development of accessory drives and powerplant systems for advanced aerospace applications, the need for reliable bearings and lubricants has become of prime importance. The low starting torque, simplicity of design, and high reliability of rolling-element bearings make them ideally suited for turbine driven machinery [1].**

*Member ASME.

**Refers to reference at end of text.

Rolling-element bearings operate in cryogenic environments such as in rocket engine turbopumps at very high speeds with light to heavy loads for several minutes duration, and in cooling system pumps at moderate speeds and loads for several hundred hours [1]. The bearings in these applications are cooled by direct contact with the cryogenic fluid. The bearing-load carrying surfaces are lubricated by the cages (retainers), which are fabricated from self-lubricating materials. The lubrication of bearings operating in liquid oxygen or liquid hydrogen is accomplished by providing a low shear-strength film on the bearing surfaces to maintain surface integrity and prevent welding. The rolling elements, i.e., balls or rollers, and the cage-locating face on one of the races are lubricated through direct contact with the cage. The rolling elements in turn provide a transfer film to the ball-race contacts (bearing-race running track). Because of the high contact stresses, the ball-race contacts are the most critical areas.

The most successful material used for bearing cages for cryogenic applications has been polytetraflouroethylene (PTFE) [2 and 3]. PTFE provides films having low friction coefficients. However, this material cannot be used in its pure form as a cage material because of its inherently poor strength properties, a low coefficient of thermal conductivity, and a tendency to cold flow under load. Therefore, PTFE must be compounded with other materials in order to provide more desirable physical properties.

At temperatures above 500° F, tests have indicated that bearing cage wear can be a limiting factor in the operation of bearings under the severe lubrication conditions encountered at these elevated temperatures.

Therefore, in addition to the race and the rolling-element material, careful consideration must be given to the choice of cage material. Precision bearings, such as those used for aerospace applications, are usually equipped with cages machined from copper alloys or nonmetallic phenolic materials. In some bearing applications, where marginal lubrication exists during operation, such as at high temperatures, silver-plated bronze cages have been used successfully. Phenolic materials are limited to temperatures of approximately 250° F, whereas copper-base alloys are suitable for operation to approximately 600° F. Above 600° F, some success has been obtained with low-carbon steel or cast-iron cages, but, generally, the most successful high-temperature cages have been nickel-base alloys. One of the nickel-base alloys used is S-Monel [1].

Other materials which have shown promise are high-temperature plastics which exhibit low friction and wear characteristics, high-alloy steels capable of maintaining their hot hardness at elevated temperatures, and stainless steels.

The objectives of the research described in this paper, which is based on the work reported initially in [4 and 5], were:

(a) To determine the film-transfer capabilities of self-lubricating cage materials for cryogenic applications by measurement of the film thickness on the bearing race grooves.

(b) To determine the capability of various cage materials for operation at temperatures of 500° and 700° F, and

(c) To investigate wear and failure mechanisms of cages in the cryogenic enviroinment, and materials factors affecting cage wear at the elevated temperatures.

APPARATUS

The bearing test apparatus shown in Fig. 1 was initially described in [2]. The test bearing is driven through a gear assembly by a variable-speed direct-currect motor. Automatic speed control can be provided over a range of test-shaft speeds from 900 to 52,500 rpm. The test shaft was supported at its lower end by the test bearing and at its upper end by a ball bearing. Thrust load was applied to the test-bearing housing from a deadweight load.

The test bearing was cooled by a direct stream of hydrogen gas from a self-pressurized liquid-hydrogen Dewar. The liquid hydrogen from the Dewar was vaporized to the desired gaseous phase in a shell-tube-type heat exchanger. Hydrogen gas at ambient temperature counterflowing in the shell of the heat exchanger was utilized as the vaporizing agent. The cryogenic hydrogen-gas flow was measured with an orifice flowmeter in a range from 0.014 to 0.031 pound per second. After flowing through the test bearing, the coolant gas was exhausted from the test chamber through the vent line. Copper-constantan thermocouples were used to measure cryogenic temperatures (a) at the test-bearing outer race, (b) in the coolant-gas supply line downstream from the orifice flowmeter, (c) in the vent line adjacent to the bearing test chamber, and (d) in the inlet and outlet lines of the heat exchanger.

For the 500° and 700° F temperatures, a cage compatibility tester was used (Fig. 2). This tester, initially described in [6], comprises three equally spaced 1/2-inch-diameter balls interposed between a flat upper race and a lower race and positioned by a test cage. Loading and drive are supplied through a drive shaft coupled to an upper race housing.

The test cage is supported on the stationary lower race and is centered about a cage guide post which is eccentric with respect to the axis of the rotating upper race. The balls are loaded against tapered cage pockets by their variation in linear speed as they orbit around the track on the stationary lower race and by centrifugal force. However, tests are not run at a speed high enough for the centrifugal force on the balls to be an appreciable fraction of the normal ball to race load.

A nitrogen atmosphere is maintained in a lubricant supply source and around the test system. A once-through lubrication system is used. The lubricant flow rate to the test cage is maintained by an oil-drip cup so that the oil level in a lubricant reservoir is kept above the lower race-ball contact.

MATERIALS AND PROCEDURE

The bearings used in the low temperature tests were 40-millimeter-bore (108 series) deep-groove bearings manufactured to ABEC-5 tolerances. One shoulder on the outer race was relieved to make the bearings separable. The inner- and outer-race curvatures were 0.54, and the average radial clearance was 0.0025 inch. The ball and the race material was AISI 440C stainless steel.

The seven cage materials investigated were the following: (a) laminated-glass cloth with PTFE binder, (b) glass-fiber-molybdenum disulfide-filled PTFE, (c) glass-fiber-filled PTFE, (d) bronze-filled PTFE, (e) copper-PTFE-tungsten diselenide composite, (f) silver-PTFE-tungsten diselenide composite, and (g) molybdenum disulfied-filled polyimide polymer. The cage designs, all of which were inner race located, are illustrated in Fig. 3. Cage material, composition, and construction are tabulated in table 1.

For the high temperature tests in the cage compatibility tester, six test cage materials were investigated: S-Monel, a copper alloy, a cobalt alloy, AISI M-1 steel, a polyimide polymer, and a modified 440C stainless steel. The chemical compositions of these materials are given in table 2. The hardness of the S-Monel, AISI M-1 and the modified 440C stainless steel materials was varied. The softer materials of these alloys tended to have larger, more numerous precipitated carbides and greater definition of tempered martensite. All six of the materials were selected for high-temperature evaluation because of their availability, their usage in current bearing application, and/or their desirable properties.

The high temperature cage materials were evaluated with two lubricants, a super refined naphthenic mineral oil and a 5P4E polyphenyl ether. The properties of these lubricants are given in table 3. These lubricants were selected for operation with the cage materials because of their practical interest as potential high-temperature lubricants.

The high temperature tests were conducted for durations of 30 to 120 minutes at 1200 rpm under a nitrogen environment, a system load of 1000 pounds, and temperatures of 500° and 700° F. The three elliptical wear scars produced in the test cage pockets at each set of conditions were measured and averaged. For any set of test conditions, the measured wear area could vary as much as ±40 percent of the average value.

For cryogenic testing the test bearing was degreased, inspected, measured for clearances (transverse surface profiles of the inner- and outer-race grooves were made with the surface profile measuring instrument), and stored in a vacuum-desiccator chamber prior to testing. The bearing was installed and the test system was purged. After the purge operation, cold hydrogen gas was force-fed to the bearing. The test shaft was rotated at 900 rpm during the cool-down period. After cool-down, a 200-pound thrust load was applied, and the bearing and shaft speed was increased to 20,000 rpm (in 5000 rpm increments every 5 minutes). The 200-pound thrust load produced maximum Hertz stresses of 230,000 and 213,000 psi for the inner and outer races, respectively.

The coolant-gas temperature to the bearing was maintained at a constant 60° R. Bearing tests were terminated when the rise in outer-race temperature could not be stabilized by increasing coolant-gas flow. The flow range of coolant gas supplied to the test bearing was from 0.014 to 0.031 pound per second for these tests. The coolant gas supply pressure to the test bearing ranged from 18.5 to 27.5 psia.

A 250-gallon supply of liquid hydrogen provided enough coolant gas for a test-run time of approximately 2 hours after the cool-down period. A test series for a bearing consisted of approximately 10 hours running time. However, a test series was ended prematurely when mechanical damage to the cage occurred.

After each test the bearing was inspected for wear and weighed to determine the weight loss or gain (in mg) of each component. The balls, races, and cages were examined visually and with optical microscopy to help determine the extent of wear and surface damage. Profile traces were made on the inner-race grooves in the ball-track region for evaluation of the formation and life histories of the transfer films (see Fig. 4). Each successive profile trace of an inner-race groove was made in approximately the same location as the initial prerun trace.

For the high-temperature cage tests in the compatibility tester, all mating surfaces were subjected to a surface-finish and hardness inspection. Hardnesses were measured in the Rockwell C or B scales and then converted to the Rockwell A scale for comparison purposes. All test-section components were scrubbed with ethyl alcohol, wiped dry, and assembled in the tester. The major and minor axes of the wear scar on each test cage pocket were measured at half-hour intervals by disassembling the tester. The size of the elliptical wear scar area produced in the cage pocket was used as the criterion for evaluating the performance of a cage material. Coking of the lubricant makes cage weight loss a less accurate indicator of wear than measurements of the wear scar.

RESULTS AND DISCUSSION

Transfer Films in Cryogenic Environment

A summary of test results is given in table 4. Successive traces of the inner-race groove of bearing A with the laminated-glass cloth with PTFE binder cage material are shown in Fig. 5. After a 284-minute run time, a substantial film was established. The scratches that appear in the film are indicative of abrasion. Continued running resulted in film breakdown and inner-race surface wear (Fig. 5(d)).

The breakdown of the transfer film was probably caused by abrasive glass particles broken away from the glass cloth in the cage ball pocket by the rubbing action of the ball. The cage material initially deposited by the balls on the race groove was probably composed largely of PTFE, which is the softer material. After a 284-minute run time, the PTFE between the glass-cloth layers had worn away leaving the glass exposed to the rubbing action of the balls. With continued running the glass fibers shredded away from the cloth and adhered to the film on the ball. Since an appreciable amount of the material transferred to the race was now abrasive glass fibers, the deposited film was worn away faster than it could be reformed by the PTFE; consequently, heavy race-groove wear resulted.

Successive profile traces of the inner-race grooves for bearings run with cages made from glass-fiber-molybdenum disulfide-filled PTFE, glass-fiber-filled PTFE, bronze-filled PTFE, and the copper composite were also made. The traces at the end of each test series are shown in Fig. 6. It can be seen that adequate transfer films were provided from each of these materials. However, the test run with the copper composite was terminated prematurely because of high cage wear.

No transfer film could be measured with the silver composite after a 117-minute run time. No subsequent traces with this material were made because the cage failed after 234 minutes of operation with bearing K. Bearing J with this cage material could not be disassembled after 138 minutes of operation. The silver composite material of bearing K demonstrated a relatively high wear value of 3.53-percent weight loss after 234 minutes operation.

Cryogenic Cage Wear

The first four materials listed in table 4 exhibited the lowest wear of the seven materials investigated. Percent weight loss for each of these four materials is plotted in Fig. 7 as a function of total sliding distance of the cage inner diameter. (Sliding distance represents the relative distance that a reference point on the cage inner diameter slides with respect to the inner-race contacting surface.)

The maximum weight loss was 0.25 percent or less of the original cage weight for each of the first four materials except with bearing H. This bearing with the bronze-filled PTFE had a weight loss of 0.89 percent for a 581-minute run time. This high wear value was attributed to the eccentric shape of the cage, which rubbed heavily on the inner-race land. It is evident from these results that in order to minimize cage wear and ensure free bearing rotation at cryogenic temperatures the possibility of high loads on the cage wearing surfaces must be reduced. This can be accomplished by provision of optimum initial clearances, both at the locating surface and in the ball pockets, and concentric surfaces between the cage and the race land.

The molybdenum disulfide-filled polyimide cage of bearing L had a wear value of 0.76-weight-percent for the relatively short life of 54 minutes. The run with this bearing was terminated due to failure which was indicated by a rapid rise in outer-race temperature. The cage of bearing M failed completely after running 22 minutes.

Cryogenic Cage Failure Mechanisms

Seven of the thirteen test series in the program were terminated prematurely because of mechanical damage to the bearing cages (table 4). Mechanical damage resulted from either (a) structural deficiency of the material, (b) improper retainer design, or (c) high wear of the material.

After a 349-minute run, the laminated-glass cloth cage with PTFE binder of bearing B delaminated between two ball pockets on the outer diameter of the retainer. The laminate separation was initiated at either a rivet hole holding the two piece cage together or at the ball-pocket wall. Delamination probably resulted from insufficient PTFE binder between adjacent glass-cloth layers or an improper curing technique in the laminating process.

Failure of the glass-fiber-filled PTFE is believed to be caused by the cage body shrinking away from the aluminum shroud at the outer diameter, between adjacent rivets, when the bearing was cooled to -400° F. When the bearing was subsequently run at 20,000 rpm, the centrifugal growth of the glass-filled PTFE between the restraining rivets caused fracture in the material at the thin web sections of the ball pocket. Cracking at the thin sections of the retainer ball pockets was also experienced with this material in several preliminary runs when the bearings were operated at high speeds (1.6 million DN value and above) in cold hydrogen gas.

Another problem which was encountered was the movement of the shroud relative to the cage body in the cages made from the silver and the copper composites and the molybdenum disulfide-filled polyimide. The combination of larger-than-required inner-land clearances and poor wear resistance of these materials resulted in an unbalanced running condition. The shroud thus rubbed against the balls causing extensive wear and jamming of the bearing. It is assumed that friction on the outer-race land was the direct cause of the shroud movement and subsequent failure. This problem could be eliminated by restraining the shroud, with pins 180° apart, integral with the cage body.

Adhesive wear [7] was evident on most of the inner-race running tracks and on several ball running tracks. Under the test conditions in this investigation, adhesive wear probably occurred on the inner-race and the ball running tracks after the initial oxide films had worn away but before a continuous lubricant film was established from transferred cage material.

Comparison of High Temperature Cage Materials

Results of 30 minute tests at a test temperature of 500° F with a naphthenic mineral oil as the lubricant for the six materials listed in table 2 are shown in Fig. 8(a). At this set of conditions, four materials show promise of operating for extended periods of time: M-1, S-Monel, modified 440C stainless steel, and the basic polyimide polymer. Tests were also conducted at 700° F with the same materials but with the 5P4E polyphenyl ether as the lubricant. The results of these tests are shown in Fig. 8(b). At this condition, the M-1, S-Monel, and 440C stainless-steel materials show the greatest promise. The high wear with the polyimide is not totally unexpected inasmuch as thermal degradation of this polymer begins at 700° F [8]. The addition of 15 percent by weight graphite to the basic polyimide polymer had no effect on the wear results at 500° F.

In both the 500° and the 700° F tests, the M-1 and S-Monel materials exhibited the least amount of wear relative to the other materials. It thus can be concluded that for elevated-temperature bearing applications M-1 and S-Monel of Rockwell A hardnesses 81 and 67, respectively, have potential bearing cage application.

Effect of Hardness on Cage Wear

The bar graphs in Fig. 9 show the results of varying hardness on cage wear for three materials, S-Monel, M-1 and 440C stainless steel, with the naphthenic mineral oil and the 5P4E polyphenyl ether as lubricants at 500° and 700° F, respectively. Wear was less for the harder S-Monel and M-1 materials. However, for the small difference in hardness of the modified 440C stainless-steel materials, there was apparently no significant difference in wear.

In addition to heat-treatment effects on material hardness, operating temperature also affects hardness. Increasing the operating temperature will, of course, decrease material hot hardness. The effect of increasing temperature from 500° to 700° F with M-1 and S-Monel cage materials run with the naphthenic mineral oil as the lubricant is shown in Fig. 10. These results show that wear will increase several times, depending on the material and its heat treatment. The Rockwell A hardness for M-1 and S-Monel decreases approximately 1 and 0.5 point, respectively, because of the increase in temperature from 500° to 700° F. These differences in hardness are not sufficient to account for the marked increases in wear indicated by the data presented in Fig. 10. Further, at 700° F, the wear magnitudes were greater with the super-refined naphthenic mineral oil than with the 5P4E polyphenyl ether. It can, therefore, be concluded that, with the S-Monel and M-1 materials, temperature affects the amount of wear through its effect on the lubrication process.

From these results it can also be concluded that, in general, potential high-temperature cage materials of the types reported herein should be heat-treated to their maximum room-temperature hardness, while sufficient ductility to prevent cracking is maintained. In application, however, the rolling-element material should be somewhat harder than the cage material to prevent damage to the rolling elements.

Wear Rate

Under marginal lubricating conditions cage wear can be a limiting factor in bearing operation. Therefore, material wear rate becomes important. The effect of running time on wear of the S-Monel and the M-1 materials at 500° F run with the mineral oil as the lubricant is shown in Fig. 11(a). For both materials, wear rate decreases with running time. It is speculated that eventually the wear rate would level off at a low level and remain constant. These data are consistent with sliding wear data, which show a decrease in the wear rate with time [1].

The results at 700° F with the polyphenyl ether with the same two cage materials are shown in Fig. 11(b). For the S-Monel and the M-1 materials, the wear rate is apparently constant.

SUMMARY

Bearing cages manufactured from seven self-lubricating materials were evaluated in 40-millimeter-bore ball bearings running in hydrogen gas at 60° R. The bearings were operated at 20,000 rpm with a 200-pound thrust load for periods up to 10 hours. The film-transfer characteristics and wear resistance of the cage materials were determined by highly magnified surface profile traces, visual observations, and weight differential measurements of the bearing components. The capabilities of six bearing-cage materials were evaluated in a cage compatibility tester at temperatures of 500° and 700° F. The effect of material hardness and temperature was investigated. The following results were obtained:

1. In the cryogenic temperature region, profile traces of bearing inner races indicated that cages made from glass-fiber-filled PTFE and bronze-filled PTFE materials maintained transfer films on the inner-race

running tracks for periods exceeding 10 hours and thereby prevented inner-race wear.

2. At temperatures of 500° and 700° F, S-Monel and AISI M-1 materials gave least wear relative to four other cage materials studied at these temperatures. For the S-Monel and AISI M-1, wear was less for higher material hardness.

3. Minimum cage wear was obtained at cryogenic temperatures with laminated-glass cloth PTFE and filled PTFE materials.

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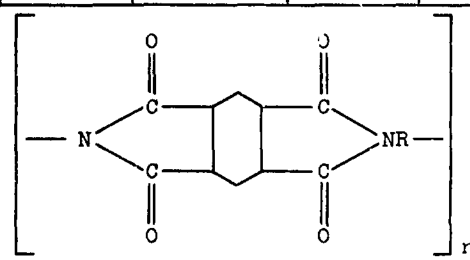
TABLE 1. - TEST-BEARING CAGES

[Deep-groove ball bearings, 40-mm bore, separable at outer race; races and balls, AISI 440C stainless steel; number of balls, 10; ball diameter, 0.375 in.; inner- and outer-race curvature, 0.54; radial clearance, 0.0025 in.; average land clearance, 0.021 in.; average ball pocket clearance, 0.017 in.]

Bearing designation	Cage material	Composition, percent weight	Cage construction
A B	Laminated-glass cloth with PTFE binder	38 Percent glass cloth laminates with 62 percent PTFE binder[a]	One-piece body with riveted aluminum side plates (fig. 3(b))
C D	Glass-fiber - molybdenum disulfide filled PTFE	15 Percent glass fibers, 5 percent molybdenum disulfide, 80 percent PTFE[a]	One-piece body with no external support (fig. 3(a))
E F	Glass-fiber-filled PTFE	15 to 20 Percent glass fibers, balance PTFE[a,b]	One-piece body with one-piece riveted aluminum shroud (fig. 3(c))
G H	Bronze-filled PTFE	30 Percent bronze powder, 70 percent PTFE[a]	One-piece body with no external support (fig. 3(a))
I	Copper composite	78 Percent copper, 9 percent PTFE, 13 percent tungsten diselenide[c]	Shrink-fit one-piece stainless-steel shroud over one-piece body[d] (fig. 3(c))
J K	Silver composite	85 Percent silver, 5 percent PTFE, 10 percent tungsten diselenide[c]	Same as copper-composite cage
L M	Molybdenum disulfide-filled polyimide	85 Percent polyimide, 15 percent molybdenum disulfide[a]	Shrink-fit one-piece aluminum shroud over one-piece body without rivets (fig. 3(c))

[a]Manufacturer's data.
[b]Less than 1 percent ferric oxide added as coloring agent.
[c]Metal composites weight percent calculated from measured specific gravity values.
[d]Shroud pinned in two places 180° apart.

TABLE 2. - CAGE MATERIALS

Material	Chemical composition, percent by weight											
	Carbon	Manganese	Silicon	Nickel	Chromium	Molybdenum	Tungsten	Vanadium	Cobalt	Copper	Iron	Other
M-1	0.75 to 0.85	0.20 to 0.40	0.20 to 0.40	---	3.75 to 4.50	7.75 to 9.25	1.15 to 1.85	0.90 to 1.30	-----	---	Bal.	---
Modified 440C stainless steel	0.95 to 1.20	1.00 Max.	1.00 Max.	---	13.00 to 16.00	3.25 to 4.25	----	----	-----	---	Bal.	---
S-Monel	0.25 Max.	0.50 to 1.5	3.5 to 5.0	62 to 68	-----	----	----	----	Trace	Bal.	3.5 Max.	---
Copper alloy	----	----	0.40 to 0.80	2.0 to 3.5	-----	----	----	----	-----	Bal.	---	---
Cobalt alloy[a]	0.09	1.0 to 2.0	1.0 Max.	10	20	----	15	----	Bal.	---	3.0 Max.	1
Polyimide polymer												

[a]Includes phosphorous, 0.04; sulfur, 0.03.

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TABLE 3. - TEST LUBRICANTS

Base stock	Additive content	Viscosity, cs			
		100° F	210° F	500° F	700° F
Super-refined naphthenic mineral oil	Oxidation inhibitor, extreme pressure additive, antifoam agent	79	8.4	1.1	0.60
5P4E Poly-phenyl ether	No additive	365	13.1	1.2	0.65

TABLE 4. - SUMMARY OF CRYOGENIC TEST RESULTS

[Test conditions: Shaft speed, 20 000 rpm; thrust load, 200 lb; coolant flow rate, 0.014 to 0.031 lb/sec hydrogen gas at 60° R; maximum Hertz stress, 230 000 psi (inner race) and 213 000 psi (outer race).]

Cage material	Bearing designation	Total test time, min	Test time at 20 000 rpm, min	Cage		Post-test bearing condition		
				Wear, percent weight	Sliding distance at inner race, ft	Cage	Inner race	Balls
Laminated-glass cloth with PTFE binder	A	628	545	0.18	3.33×10^{6}	Very good	Adhesive wear	Scuff marks on wear track
	B	343	300	0.11	1.84×10^{6}	Delaminated	Adhesive wear	Scuff marks on wear track
Glass-fiber - molybdenum disulfide-filled PTFE	C	615	518	0.19	3.19×10^{5}	Very good	Slight adhesive wear	Transfer film on wear track
	D	618	500	0.25	3.09×10^{6}	Very good	Wide wear track with transfer film	Dark, hammered effect over entire surface
Glass-fiber-filled PTFE	E	464	400	0.06	2.45×10^{6}	Cracked	Adhesive wear with scuff marks	Scuff marks on wear track and adhesive wear
	F	580	500	0.17	3.04×10^{6}	Very good	Transfer film, no adhesive wear	Transfer film on wear track
Bronze-filled PTFE	G	575	500	0.16	3.07×10^{6}	Very good	Bronze-colored film, no adhesive wear	Bronze-colored film on wear track
	H	581	501	0.89	3.08×10^{6}	High wear	Heavier bronze-colored film than on bearing G	Heavier bronze-colored film than on bearing G
Copper composite	I	213	176	2.96	1.08×10^{6}	High wear	Copper-colored film, slight adhesive wear	Copper-colored film over entire surface
Silver composite	J	138	120	----	0.73×10^{6}	Balls rubbed shroud	Race not separable	Silver-colored film, some scuff marks
	K	234	200	3.53	1.216×10^{6}	High wear and cracked	Silver-colored wear track with some adhesive wear	Silver-colored film
Molybdenum disulfide-filled polyimide	L	54	15	0.76	---------	High wear	Wide, dark-colored wear track with adhesive wear	Dark film over entire surface with adhesive wear
	M	22	0	----	---------	Destroyed	Bearing seized	Bearing seized

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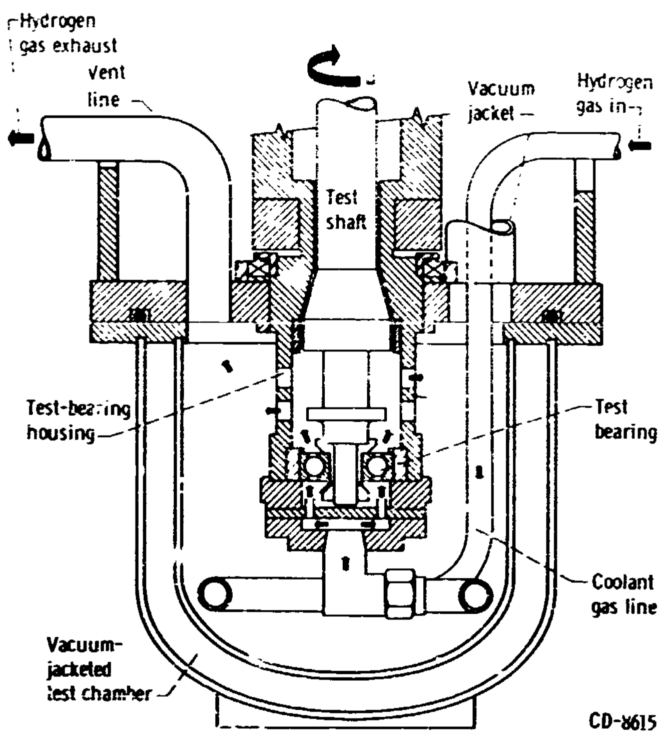

Figure 1. - Schematic of bearing test apparatus.

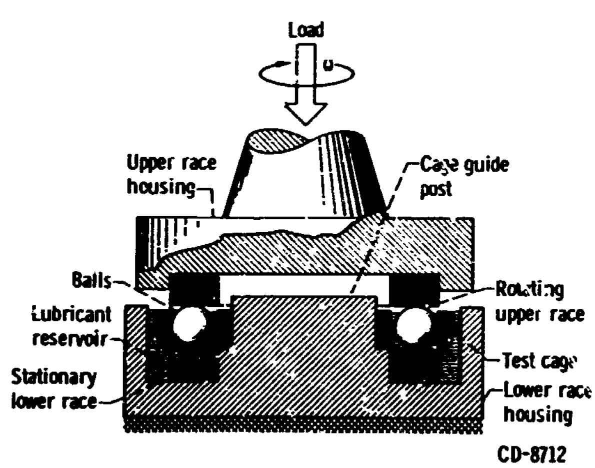

Figure 2. - Cage compatibility tester.

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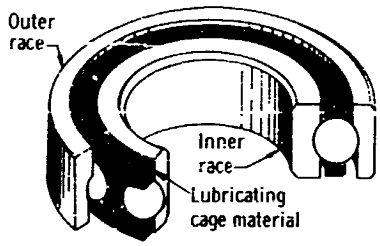
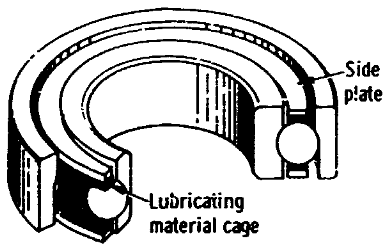
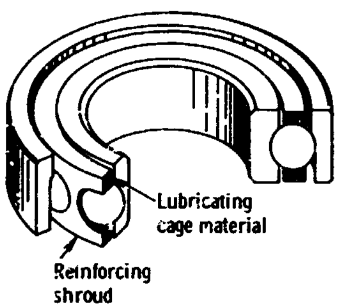


(a) One-piece body with no external support.



(b) One-piece body with side plates.



(c) One-piece body with one-piece shroud.

Figure 3. - Test-bearing cage designs.

E-3422

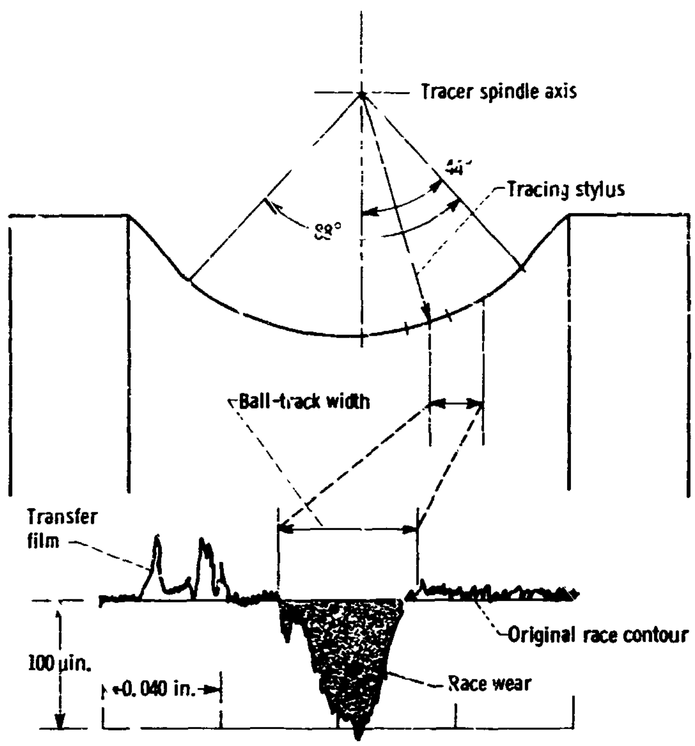


Figure 4. - Profile trace of bearing inner race normal to ball-rolling direction.

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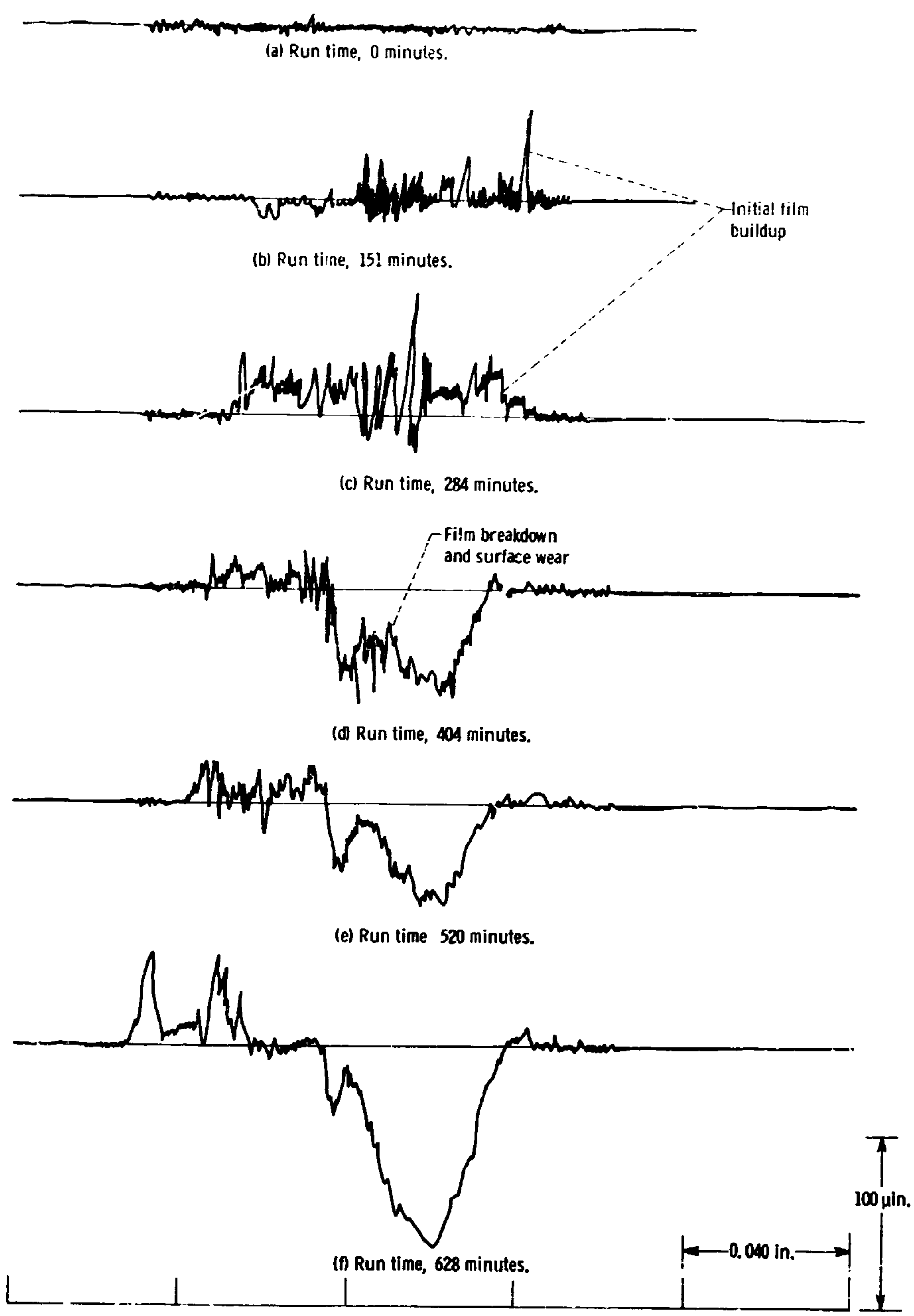

Figure 5. - Progressive profile traces of inner-race groove of bearing A with a laminated-glass cloth with PTFE binder cage material. Shaft speed, 20 000 rpm; thrust load, 200 pounds; coolant, hydrogen gas at 60° R.

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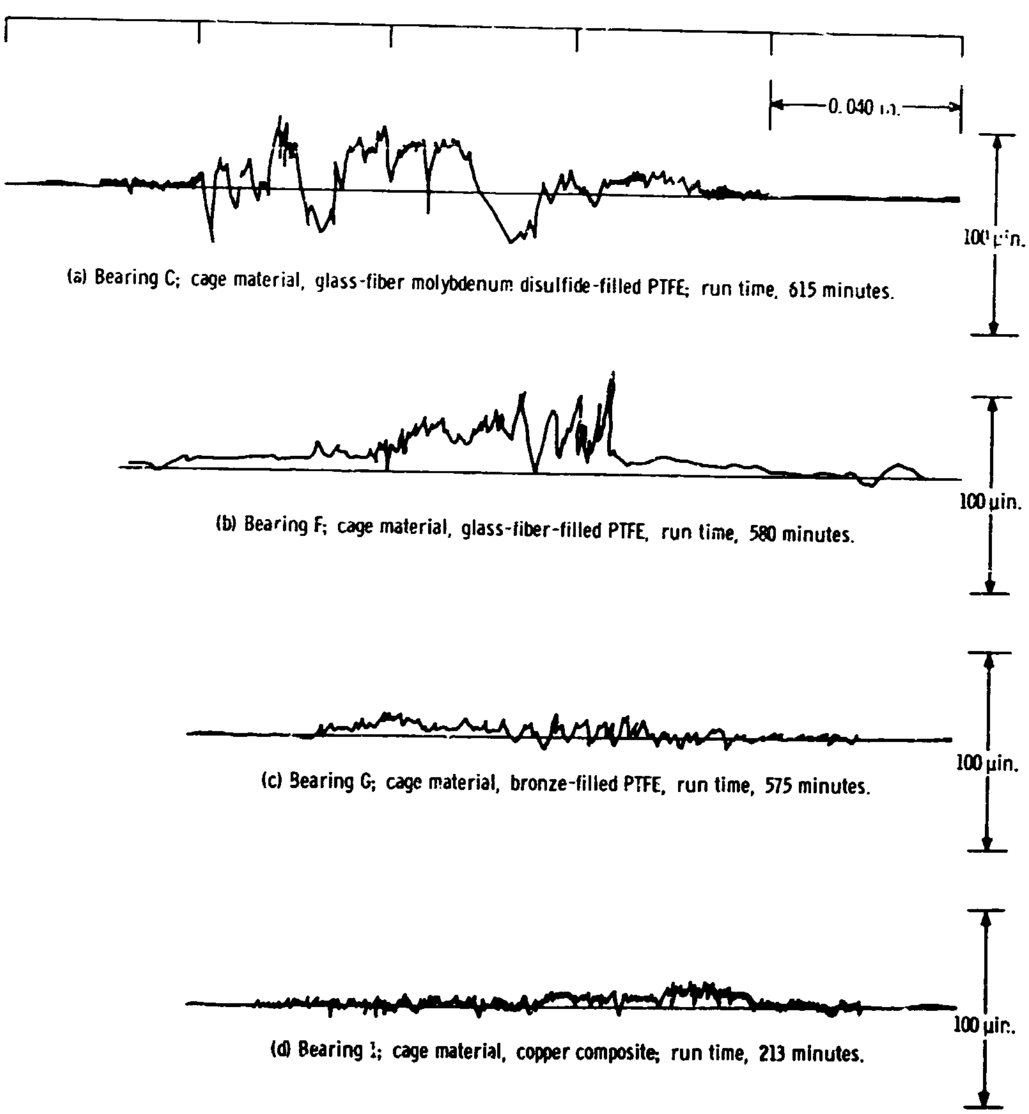

(a) Bearing C; cage material, glass-fiber molybdenum disulfide-filled PTFE; run time, 615 minutes.

(b) Bearing F; cage material, glass-fiber-filled PTFE, run time, 580 minutes.

(c) Bearing G; cage material, bronze-filled PTFE, run time, 575 minutes.

(d) Bearing 1; cage material, copper composite; run time, 213 minutes.

Figure 6. - Profile traces of inner-race grooves for bearing run with different cage materials. Shaft speed, 20 000 rpm; thrust load, 200 pounds; coolant, hydrogen gas at 60° R.

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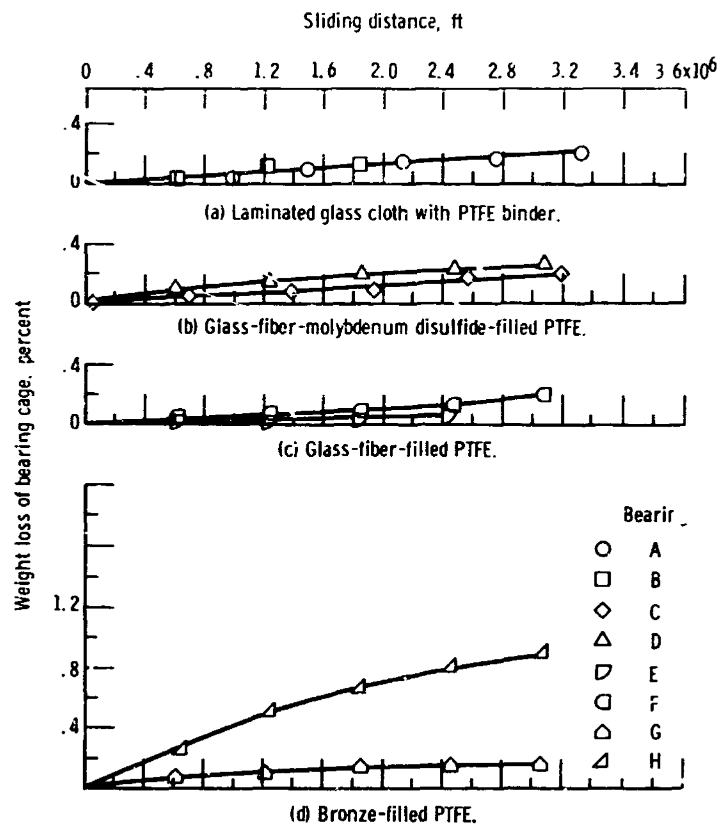

Figure 7. - Bearing cage weight loss as a function of sliding distance relative to inner race. Shaft speed, 20 000 rpm; thrust load, 200 pounds; coolant, hydrogen gas at 60° R.

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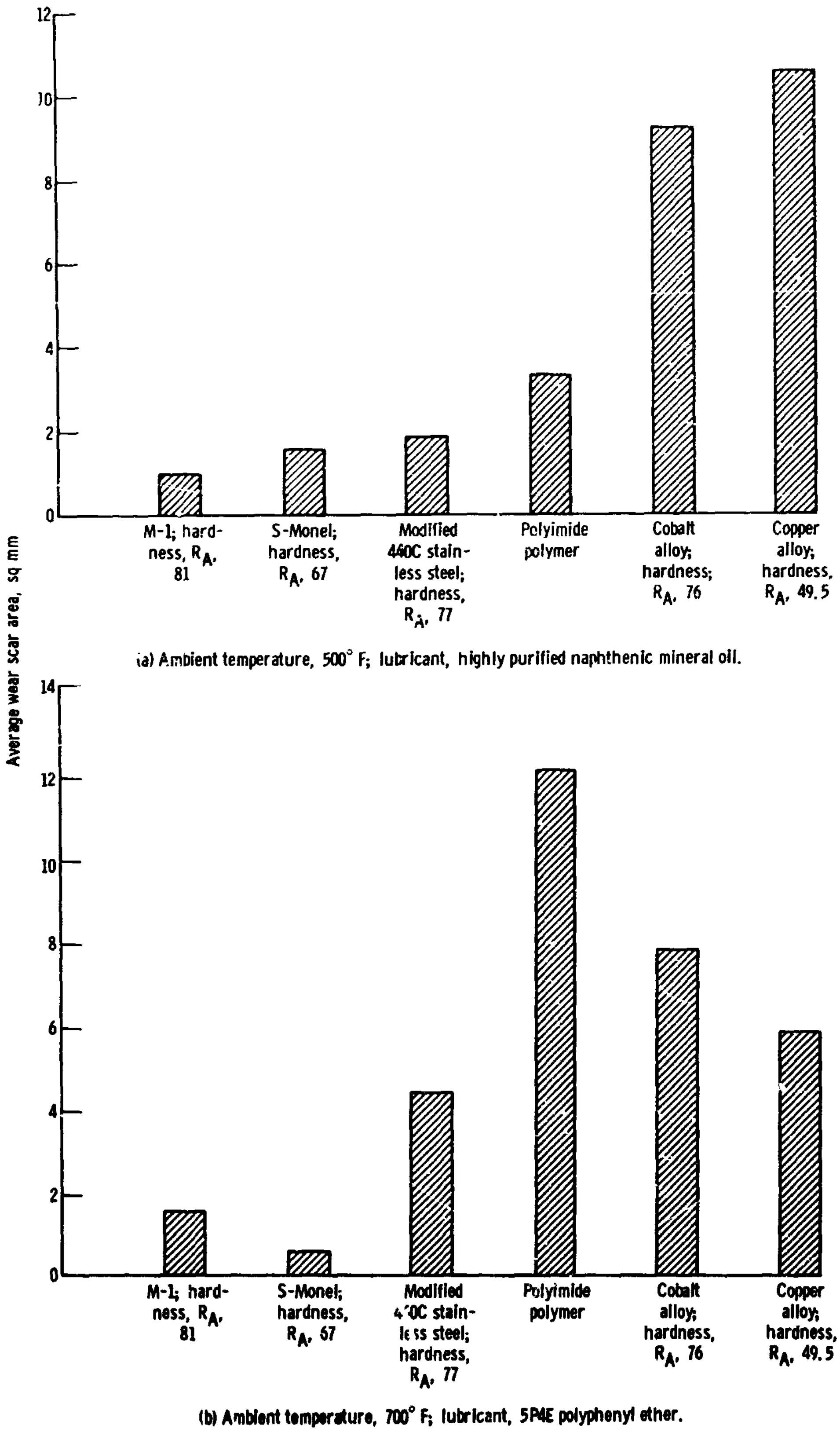

Figure 8. - Wear of various materials in inert environment. Shaft speed, 1200 rpm; system load, 1000 pounds; duration, 30 minutes; room temperature hardness given.

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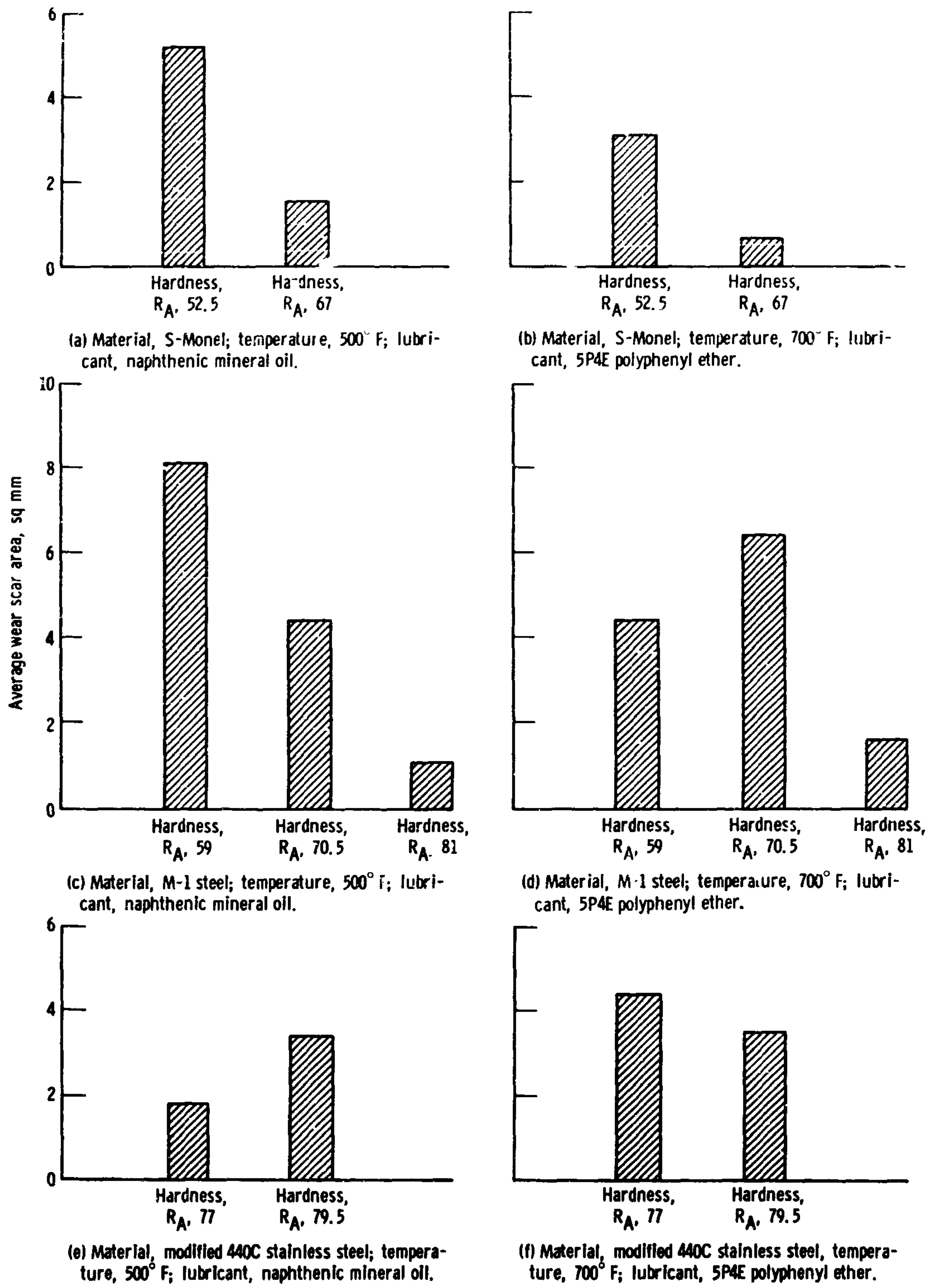


Figure 9. - Effect of hardness on cage wear. Shaft speed, 1200 rpm; system load, 1000 pounds; duration, 30 minutes.

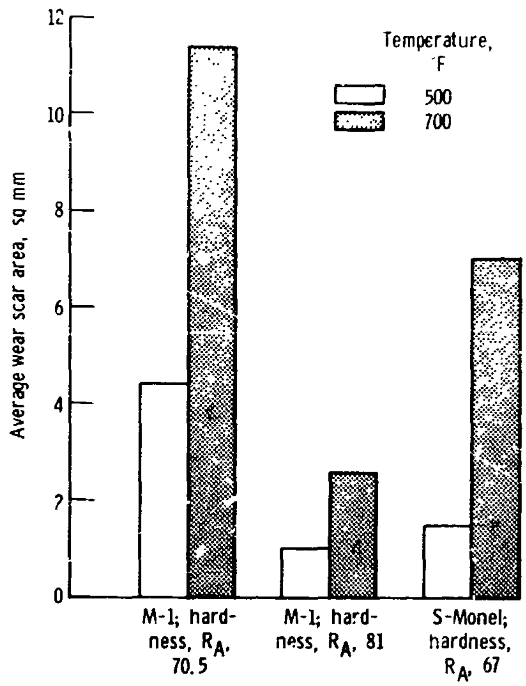
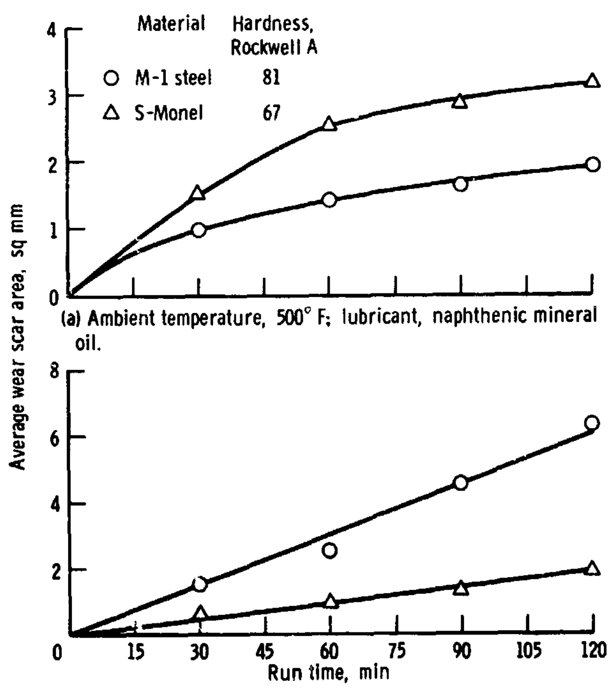


Figure 10. - Effect of temperature on cage wear for M-1 and S-Monel with naphthenic mineral oil. Shaft speed, 1200 rpm; system load, 1000 pounds; duration, 30 minutes.



(b) Ambient temperature, 700° F; lubricant, 5P4E polyphenyl ether.

Figure 11. - Effect of running time on cage wear. Shaft speed, 1200 rpm; system load, 1000 pounds.